

## **GAS SENSOR AND MANUFACTURING METHOD THEREOF**

### **I. DESCRIPTION**

#### **I.A. Related Applications**

[01] This Application claims foreign priority from JP 2003-066108, filed March 12, 2003, the contents of which are incorporated herein by reference.

#### **I.B. Field**

[02] The present disclosure teaches techniques related to a gas sensor. More specifically, it relates to a novel gas sensor having superior long term stability and superior gas selectivity to a volatile organic compound at a temperature of 100°C or less using a particular organic-inorganic hybrid material as a sensor element. For example, the disclosed teachings are useful for providing a volatile organic compound (VOC) gas sensor and the like. Such a gas sensor, for example, does not respond to a flammable gas such as hydrogen and responds selectively to a VOC gas.

#### **I.C. Background**

##### **1. Related Work**

[03] Sick house syndrome has become a problem as people spend more time indoors with less ventilation. The sick house syndrome is often caused by volatile organic compounds (VOC) released from building materials, furniture, paints, adhesives, and the like. VOC sensors are required to monitor indoor environments. Gas sensors using an n-type semiconductor oxide such as tin oxide, for example, have superior long term stability. Further, they can be miniaturized and do not require any expensive devices for the production

and complicated circuits for sensing the change in resistance. Therefore, these sensors have been widely used in practice as household gas leak alarms and the like. Furthermore, research is being carried out related to semiconductor gas sensors for detecting various gases in addition to household gases are being used. Specifically, gas sensors for sensing VOC is being studied. . Gas sensors that selectively sense only one gas is required.

[04]           However, it is difficult to make semiconductor oxide gas sensors that selectively detect various gases. VOC sensors using a semiconductor oxide known in the related are sensors that sense the total volume of some ten types of VOC. In order to improve the gas selectivity, for example, a method for providing a catalytic layer on a surface of a semiconductor oxide is described in JP 2000-298108 and JP 2000-292397. In addition, a method for coating a surface of a semiconductor oxide with a silica film used as a filter layer is described in JP 10-170464 and JP 2000-275201. Further, a method for adding a noble metal or an oxide to tin oxide is discussed in IEEJ Transactions E, 119, 383-389 (1999) and IEEJ Transactions E, 121, 395-401 (2001).

[05]           However, further improvement in gas selectivity is required. In addition, development of VOC gas sensors using a conductive polymer has also been reported. Although the gas selectivity has been improved (see JP 08-015197) compared to that of semiconductor gas sensors, improvement in long term and thermal stability is a major issue.

[06]           Furthermore, in a resistance change type sensor using a conductive polymer, in order to avoid polarization, the change in impedance must be measured by applying an alternating current. Accordingly, as compared measuring using direct current, the circuit becomes more complicated.

[07]           Although examples of VOC sensors exist, further improvement is required. High performance gas sensors having superior gas selectivity is required.

## II. SUMMARY

[08] It will be significantly advantageous to overcome problems noted above in related art.

[09] There is provided a gas sensor comprising a sensor element including an organic-inorganic hybrid material. The hybrid materials have a layered structure in which an organic compound is intercalated into layers of an inorganic compound.

[10] In a specific enhancement, presence of a gas is detected by a change in resistance.

[11] In another specific enhancement, the inorganic compound comprises molybdenum oxide.

[12] In another specific enhancement the organic compound comprises a conductive polymer.

[13] In yet another specific enhancement, the gas sensor responds to a volatile organic compound at a temperature in the range of from room temperature to 80°C.

[14] In still another specific enhancement, the inorganic and organic individual layers have thickness less than 1 nano meters and they are alternately laminated to each other.

[15] Another aspect of the disclosed teachings is a method for manufacturing a gas sensor comprising providing layers of an inorganic compound. An organic compound is intercalated between the layers of the inorganic compound to form a organic-inorganic hybrid material. The hybrid material is used as a sensor element in the gas sensor.

[16] Still another aspect of the disclosed teachings is a method of manufacturing a hybrid organic-inorganic material comprising suspending an inorganic material in distilled water in an argon atmosphere. Sodium dithionate and a sodium salt are added and stirred. The inorganic material with hydrated sodium ions intercalated between layers of the oxide product is separated, washed and dried. The product is suspended in distilled water; A

monomer is added and stirred. An oxidizing agent is added and stirred. The product is separated.

[17] In a specific enhancement, the oxidizing agent is selected from a group consisting of iron chloride, ammonium peroxodisulfate and iron nitrate.

[18] In another specific enhancement, an amount of the monomer is 50 to 200 equivalents to one equivalent of the hydrated sodium ions intercalated material.

[19] More specifically, the amount of conductive polymer is 100 to 150 equivalents to one equivalent of the hydrated sodium ions intercalated material.

[20] In another specific enhancement, the inorganic material is selected from a group consisting of molybdenum oxide, tungsten oxide, vanadium oxide, niobium oxide, ruthenium chloride, iron oxychloride and molybdenum sulfide.

[21] In yet another specific enhancement, the conductive polymer is selected from a group consisting of polypyrrole, polyaniline, polythiophen and polyethyleneoxide.

### III. BRIEF DESCRIPTION OF THE DRAWINGS

[22] The disclosed teachings will become more apparent by describing in detail examples and embodiments thereof with reference to the attached drawings in which:

[23] Fig. 1 is a schematic view showing one example of a crystal structure of a gas sensor material according to the disclosed teachings.

[24] Fig. 2 is a graph showing x-ray diffraction patterns of  $[\text{Na}(\text{H}_2\text{O})_5]_x\text{MoO}_3$  and  $\text{PPy}_y\text{MoO}_3$  described in Example 1.

- [25] Fig. 3 is a graph showing infrared spectra of  $[\text{Na}(\text{H}_2\text{O})_5]_x\text{MoO}_3$ ,  $\text{PPy}_y\text{MoO}_3$ , and simple polypyrrole (PPy) prepared by a chemical polymerization method described in Example 1.
- [26] Fig. 4 is a graph showing the results of thermogravimetric analysis of  $\text{PPy}_y\text{MoO}_3$  and simple polypyrrole (PPy) formed by a chemical polymerization method described in Example 1.
- [27] Fig. 5 is a graph showing sensor sensitivity of a sensor described in Example 1 to a methanol gas.
- [28] Fig. 6 is a graph showing an x-ray diffraction pattern of  $\text{PPy}_y\text{MoO}_3$  described in Example 2.

#### IV. DETAILED DESCRIPTION

##### IV.A. Synopsis

- [29] A new sensing principle which does not depend on the sensing principle of the semiconductor oxide sensor described above is disclosed herein. A novel sensor using a hybrid material obtained by nanometer-level integration of an organic material and an inorganic material is provided. The organic material is used to recognize the target gas molecules. The inorganic material is used to convert chemical information (representing whether a gas to be sensed is present or not) into an electrical signal. This information is output.
- [30] When an organic compound and an inorganic compound are allowed to perform different functions and are integrated together on a nano-scale, a sensor can be made which

has both high sensitivity of the organic compound and high stability of the inorganic compound and which can easily output a signal outside. A hybrid sensor, which is formed by a combination of an appropriate metal oxide and a conductive polymer, responds selectively to a VOC gas as the resistance is changed. It is also stable as compared to a sensor composed of only a conductive polymer.

[31]

#### **IV.B. Examples illustrating concepts underlying the disclosed teachings**

[32] The disclosed teachings are described in more detail herein.

[33] A metal oxide having a layered structure is used as the inorganic compound. An organic polymer is intercalated between these layers. The organic-inorganic hybrid sensor is formed by nanometer-level integration. The combination between the organic compound and the inorganic compound needs to be appropriately selected. For example, when combination of an organic compound and an inorganic compound, which have different types of carriers responsible for conductivity, is selected, charge transfer occurs between these two compounds. As a result, conductivity is imparted to the hybrid sensor.

[34] In the sensor described above, for example, when incorporation of a VOC gas into the organic polymer layers causes the change in the interlayer distance, the charge transfer is influenced. This changes the electrical resistance of the sensor. A hybrid material obtained by the combination of an inorganic compound having conductivity and an organic compound having insulating properties exhibits conductivity. However, since the charge transfer does not occur, the sensing function based on the principle described above cannot be expected. The sensing can be achieved only when the inorganic compound (which forms the disclosed

hybrid sensor) has a layered structure and is provided with conductivity by the charge transfer from the organic compound.

[35] An interlayer compound used for a gas sensor comprises of an inorganic compound having a layered structure and an organic compound intercalated between the inorganic layers. As one example, Fig. 1 shows a schematic view of a crystal structure of an interlayer compound. In this structure, molybdenum oxide (shown in the figure as layer 1) is the inorganic compound with a layered structure and polypyrrole (shown in the figure as layer 2) (PPy) is the organic compound.

[36] A layered structure (hereinafter, this material will be described as  $\text{PPy}_y\text{MoO}_3$ ) is formed in which polypyrrole is intercalated between layers of molybdenum oxide. Although molybdenum oxide itself is an insulating material, it is turned into an n-type semiconductor when electrons are supplied thereto. On the other hand, as in the case described above, Polypyrrole is turned into a p-type semiconductor when emitting electrons. Accordingly, conductivity is generated in  $\text{PPy}_y\text{MoO}_3$  by the charge transfer from polypyrrole to molybdenum oxide.

[37] Although  $\text{PPy}_y\text{MoO}_3$  is synthesized in the form of a powder, it can be easily molded by press molding. Hence, a sensor element can be formed by providing electrodes on the press-molded body thus formed.

[38]  $\text{PPy}_y\text{MoO}_3$  can be prepared by a two-stage reaction. First,  $[\text{Na}(\text{H}_2\text{O})_5]_x\text{MoO}_3$  is synthesized in which hydrated sodium ions is intercalated between layers of molybdenum oxide. In this stage, molybdenum oxide is suspended in distilled water in an argon atmosphere, and sodium dithionite and sodium molybdate are added thereto, followed by stirring. The reaction time is generally 5 minutes to one hour, and preferably 10 to 30

minutes. A reaction product is separated, washed, and dried, thereby obtaining  $[\text{Na}(\text{H}_2\text{O})_5]_x\text{MoO}_3$ .

[39] Next, at the second stage reaction,  $[\text{Na}(\text{H}_2\text{O})_5]_x\text{MoO}_3$  is suspended in distilled water, and pyrrole is added thereto, followed by sufficient stirring. Subsequently, an oxidizing agent is added to the mixture thus formed and the mixture is then further stirred. A reaction product is separated, washed, and dried, thereby obtaining  $\text{PPy}_y\text{MoO}_3$ . The oxidizing agent used at this stage is not specifically limited: as long as it can oxidize pyrrole. Iron chloride, ammonium peroxodisulfate, and iron nitrate are examples of oxidizing agents that can be used. The amount of pyrrole added is generally 50 to 200 equivalents and preferably 100 to 150 equivalents with respect to one equivalent of  $[\text{Na}(\text{H}_2\text{O})_5]_x\text{MoO}_3$ . The amount of the oxidizing agent added is generally 1 to 3 equivalents and preferably 1.5 to 2 equivalents with respect to one equivalent of  $[\text{Na}(\text{H}_2\text{O})_5]_x\text{MoO}_3$ .

[40] In general, an electrical resistance change type sensor composed of an n-type semiconductor oxide responds to a VOC gas as that the resistance is decreased. However, the gas sensor disclosed herein responds to a VOC gas such that a sensor resistance is increased. In particular, among VOC gases, the sensor responds selectively to polar molecules such as aldehydes and alcohols. Compared to a nonpolar molecule, a polar molecule generates a strong interaction with polypyrrole having positive charge, and hence it is believed that a polar molecule infiltrates a polypyrrole layer having the crystal structure shown in Fig. 1. As a result, the interlayer distance is increased, and the charge transfer is suppressed, resulting in increase in resistance of the sensor. That is, such a gas sensor exhibits a selective and particular response to a gas having polarity among VOC gases.

[41] Furthermore, since the disclosed sensor exhibits a response at room temperature, a heating mechanism and the like are not particularly necessary. In addition, since polarization



is not generated unlike a simple conductive polymer, resistance measurement can be performed using a direct current. Therefore, a complicated measuring circuit using an alternating current is not necessary. Accordingly, the sensor unit can be miniaturized.

[42] In addition, according to the results of a thermogravimetric analysis performed on the disclosed organic-inorganic hybrid material, the decomposition temperature of polypyrrole is increased by approximately 50°C as compared to pure polypyrrole which is formed separately. The thermal stability is improved by hybridization.

[43] Furthermore, the long term stability is also superior. Even when being held in the air for a half year or more after the formation, degradation in conductivity is not observed. A wearable VOC monitoring device can be made using the sensor disclosed herein.

[44] The disclosed techniques in which molybdenum oxide and polypyrrole are used may also be applied to a layered inorganic compound and a conductive polymer other than molybdenum oxide and polypyrrole. Examples of the layered inorganic compound capable of forming a gas sensor of the organic-inorganic hybrid material include, but not limited to, tungsten oxide, vanadium oxide, niobium oxide, ruthenium chloride, iron oxychloride, or molybdenum sulfide. Examples of the conductive polymer that can be used include polyaniline, polythiophen, or polyethylene. However, they are not limited to those mentioned above. Materials that produce the same effect as that of the above compounds may also be used.

#### IV.C. Illustrative Examples

[45] Next, the disclosed teachings will be particularly described with reference to examples; however, the teachings are not limited to the following examples at all.

1. Example 1

[46] (1) Formation of PPy<sub>y</sub>MoO<sub>3</sub>

[47] Molybdenum oxide MoO<sub>3</sub> powder (1 g, 6.9 mmol) was added to 50 ml of distilled water and was stirred for 30 minutes at room temperature while an argon gas was being bubbled. To the mixture thus formed, after sodium dithionite Na<sub>2</sub>S<sub>2</sub>O<sub>4</sub> (0.35 g, 2.0 mmol) and sodium molybdate Na<sub>2</sub>MoO<sub>4</sub>·2H<sub>2</sub>O (12 g, 49.6 mmol) were added, stirring was performed for 10 minutes at room temperature while an argon gas was being bubbled. The color of the molybdenum oxide powder quickly changed from white into deep blue upon adding sodium dithionite and sodium molybdate, and hence it was confirmed that molybdenum oxide was reduced. After stirring was performed, a reaction product was processed by vacuum filtration and was then washed with distilled water, and spontaneous drying was then performed in the air. Based on the results of the thermogravimetric analysis, it was found that x=0.17.

[48] Next, [Na(H<sub>2</sub>O)<sub>5</sub>]<sub>x</sub>MoO<sub>3</sub> (0.1 g, 0.61 mmol) formed by the method described above was suspended in 40 ml of distilled water, and after pyrrole (5.8 ml, 89.22 mmol) was added thereto, the mixture thus formed was processed using an ultrasonic homogenizer for 3 minutes. To this mixture thus processed, iron chloride FeCl<sub>3</sub> (0.146 g, 0.90 mmol) was added as an oxidizing agent and was then stirred for 10 minutes at room temperature. In addition, after 40 ml of ethanol was added and was then stirred for 20 minutes, a reaction product was processed by vacuum filtration, washed with ethanol, and spontaneously dried in the air, thereby obtaining PPy<sub>y</sub>MoO<sub>3</sub>. An x-ray diffraction pattern of the PPy<sub>y</sub>MoO<sub>3</sub> thus formed by the above process is shown in Fig. 2 together with that of [Na(H<sub>2</sub>O)<sub>5</sub>]<sub>x</sub>MoO<sub>3</sub> for comparison. In both samples, the crystallographic b axis is perpendicular to the molybdenum oxide layers,

and by observing the (0k0) peak of the x-ray diffraction pattern, the change in interlayer distance could be understood.

[49] Since the (0k0) peak of  $\text{PPy}_y\text{MoO}_3$  was shifted to the low angle side as compared to that of  $[\text{Na}(\text{H}_2\text{O})_5]_x\text{MoO}_3$ , it is understood that the interlayer distance of  $\text{PPy}_y\text{MoO}_3$  was increased. The increase in interlayer distance of  $\text{PPy}_y\text{MoO}_3$  was 0.63 nm as compared to that of simple molybdenum oxide, and this shows that polypyrrole was intercalated between the layers of molybdenum oxide.

[50] In Fig. 3, infrared spectra of  $[\text{Na}(\text{H}_2\text{O})_5]_x\text{MoO}_3$ ,  $\text{PPy}_y\text{MoO}_3$ , and polypyrrole (PPy) prepared by a chemical polymerization method are shown. In  $\text{PPy}_y\text{MoO}_3$ , absorption of molybdenum oxide, which was also observed in  $[\text{Na}(\text{H}_2\text{O})_5]_x\text{MoO}_3$ , and absorption of polypyrrole were both observed, and hence it was confirmed that a layered compound composed of molybdenum oxide and polypyrrole intercalated between the layers thereof was formed. In Fig. 4, the result of the thermogravimetric analysis of  $\text{PPy}_y\text{MoO}_3$  is shown together with that of the polypyrrole formed by a chemical polymerization method for comparison. Temperatures indicated by individual arrows are decomposition temperatures of polypyrroles. The decomposition temperature of the layered compound  $\text{PPy}_y\text{MoO}_3$  was higher than that of pure polypyrrole by approximately 60°C, and this shows that the hybridization with an inorganic compound is effective to improve the thermal stability of an organic polymer. In this figure, the decrease in weight up to approximately 100°C was caused by adsorbed water. In addition, from the decrease in weight caused by decomposition of pyrrole, as the y value of  $\text{PPy}_y\text{MoO}_3$ , y=0.3 was obtained.

[51] (2) Evaluation of Electrical Properties and Sensor Properties

[52] A sample obtained by performing press molding for  $\text{PPy}_y\text{MoO}_3$  powder thus formed was provided with electrodes using a silver paste, thereby forming a sensor element. The

electrical resistivity of the press-molded body measured by a DC four-probe method was  $9.6 \times 10^{-4} \Omega \cdot \text{cm}$  at room temperature. The electrical resistivity of a press-molded body of powdered  $[\text{Na}(\text{H}_2\text{O})_5]_x\text{MoO}_3$  measured in the same manner as that described above was  $3,200 \times 10^{-4} \Omega \cdot \text{cm}$ , and hence by intercalating polypyrrole between the layers, the electrical resistivity was decreased by two orders of magnitude or more. This shows that the polypyrrole layer has conductivity as is the molybdenum oxide layer, and that the charge transfer is realized between the molybdenum oxide layer and the polypyrrole layer.

- [53] Sensor properties of the  $\text{PPy}_y\text{MoO}_3$  sensor to hydrogen, carbon monoxide, carbon dioxide, and methane gas were evaluated by the change in electrical resistance when the sensor was exposed to the individual gases. The concentrations of the gases for evaluation were all set to 3% (balanced with air), and the measurement temperature was set to room temperature and  $100^\circ\text{C}$ . The measurement was performed by allowing clean air (one minute), a sample gas (three minutes), and clean air (16 minutes) to flow in that order, and the total 20 minutes was regarded as one cycle.
- [54] According to the measurement results, the  $\text{PPy}_y\text{MoO}_3$  sensor did not respond to these gases. On the other hand, the measurement result of the sensor properties to methanol is shown in Fig. 5. For the measurement of methanol, the sensor was placed in an airtight type chamber, and after a liquid methanol was supplied to a heater provided in the chamber for evaporation to obtain a predetermined concentration, the change in resistance of the sensor was measured.
- [55] The vertical axis in the figure indicates resistance normalized by the initial resistance. A response to methanol was shown, in which the resistance of the sensor was increased. The sensor sensitivity ( $R_{\text{gas}}/R_0$ :  $R_0$  indicates the initial resistance, and  $R_{\text{gas}}$  indicates the resistance in a gas atmosphere) to various VOC gases at a concentration of 1,000 ppm at room

temperature is shown in Table 1. The sensor hardly responded to toluene and benzene but selectively responded to aldehydes, alcohols, and a chlorinated gas. Among those mentioned above, particularly high sensitivity was shown to formaldehyde. This fact shows that the disclosed sensor hardly responds to flammable gases such as hydrogen and has high selectivity to VOC gases.

[56] Table 1

[57] Sensor Sensitivity of PPy<sub>y</sub>MoO<sub>3</sub> Sensor at Room Temperature to Various VOC Gases at Concentration of 1,000 ppm

Gas	Sensor Sensitivity ( $R_{\text{gas}}/R_0$ ), %
Formaldehyde	6.0
Methanol	0.8
Ethanol	0.7
Chloroform	2.0
Acetone	0.2
Toluene	<0.1
Benzene	<0.1

[58]

## 2. Example 2

[59] A PPy<sub>y</sub>MoO<sub>3</sub> sensor was formed in a manner similar to that described in Example 1 except that the oxidizing agent used for intercalation reaction of polypyrrole into [Na(H<sub>2</sub>O)<sub>5</sub>]<sub>x</sub>MoO<sub>3</sub> was ammonium peroxodisulfate (NH<sub>4</sub>)<sub>2</sub>S<sub>2</sub>O<sub>8</sub>. The x-ray diffraction pattern of a formed powder is shown in Fig. 6. As was the case of Example 1, it was confirmed that an interlayer compound of molybdenum oxide and polypyrrole intercalated between the

layers thereof was formed. When the sensor properties were measured, the similar results as those in Example 1 were obtained.

3. Example 3

[60]  $[\text{Na}(\text{H}_2\text{O})_5]_x\text{MoO}_3$  was formed in a manner similar to that described in Example 1 except that the reaction time for forming  $[\text{Na}(\text{H}_2\text{O})_5]_x\text{MoO}_3$  was set to three hours. According to the x-ray diffraction measurement for the  $[\text{Na}(\text{H}_2\text{O})_5]_x\text{MoO}_3$  thus formed, the generation of impurities was observed as the reaction time was increased. From the results thus obtained, it was found that the reaction time for forming  $[\text{Na}(\text{H}_2\text{O})_5]_x\text{MoO}_3$  is preferably set to 30 minutes or less.

[61] Following advantages are realized using various aspects of the disclosed teachings:

[62] (1) A novel gas sensor based on a new sensing principle which does not depend on that of a conventional semiconductor oxide sensor is provided. A manufacturing technique of the gas sensor described is also provided.

[63] (2) A novel gas sensor based on the following sensing principle is provided. That is, in an interlayer compound made of an inorganic compound and an organic compound alternately laminated to each other, the interlayer distance is changed by a gas which is to be sensed, and as a result, the sensor resistance is controlled.

[64] (3) According to the disclosed manufacturing method, a novel gas sensor composed of an interlayer compound can be manufactured, in which an inorganic compound and an organic compound are alternately laminated to each other.

[65] (4) The gas sensor thus formed hardly responds to flammable gases such as hydrogen but responds selectively to VOC gases.

[66] (5) The gas sensor thus formed is useful as a VOC sensor.

**[67]** Other modifications and variations to the invention will be apparent to those skilled in the art from the foregoing disclosure and teachings. Thus, while only certain embodiments of the invention have been specifically described herein, it will be apparent that numerous modifications may be made thereto without departing from the spirit and scope of the invention.